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TECHNICAL REPORT EE-63

A PROTOTYPE LIGHT-WEIGHT REMOTE MICROWAVE REFRACTOMETER

by

Donald C. Thorn, Wallis R. Cramond
Richard O. Gilmer, and John C. Jordan

July 1962

Prepared under
White Sands Missile Range
Contract DA-29-040-ORD-1238

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ABSTRACT

This paper describes a special microwave refractometer which conforms to severe weight and space limitations. This refractometer is designed on a somewhat different principle from previous types of refractometers. Basically, it is divided into two separate units: a self-contained transmitter and a ground unit.

The transmitting unit is designed to be packaged into the nosecone (approximately 165 cubic inches) of an ARCAS missile to be carried aloft to sound the upper atmosphere to an altitude of approximately 200,000 feet. A maximum weight requirement of 7.5 pounds is imposed upon the transmitter. Because of space and weight requirements, the transmitting unit is to have a minimum number of components. As a result, the ground unit will need an increased amount of more complex equipment.

All the information required to determine the relative index of refraction is obtained and coded by the transmitter. The ground unit receives the information transmitted by the airborne unit and must be able to amplify, decipher, and record the desired information.

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SECTION 1

INTRODUCTION AND HISTORICAL BACKGROUND

The art of microwave refractometry dates essentially from 1950. In that year, both Cullen M. Crain[1] and George Birnbaum[2] published the results of their development work at the University of Texas and the National Bureau of Standards, respectively, for X-band (approximately 9435 megacycles per second) microwave refractometers. Both the Crain (University of Texas) and Birnbaum (Bureau of Standards) refractometers have common characteristics, but are certainly distinct and different units.

The fundamental concept of refractometry, according to both of these originators, was one of measuring the changes in resonant frequency of a microwave cavity. Both devices make use of the fact that, for a given mode and dimensions, the resonant frequency of a microwave cavity is determined by the relation

$$f_o = \frac{K}{n}, \qquad (1\text{-}1)$$

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[1]Crain, C. M., "Apparatus for Recording Fluctuations in the Refractive Index of the Atmosphere," The Review of Scientific Instruments, vol. 21, No. 5, pp 456-457, May 1950.

[2]Birnbaum, G. A., "A Recording Microwave Refractometer," The Review of Scientific Instruments, vol. 21, pp 169, 1950.

in which f_o is the resonant frequency, K is a constant determined by the mode and cavity dimensions, and n is the aggregate macroscopic index of refraction of the material or materials contained within the cavity. The range of n for the earth's atmosphere ranges as

$$1.000000 < n < 1.000500 \tag{1-2}$$

in which the upper limit is less than 1.000500 and is more realistically 1.000300. Because of this range of values, it is common practice in atmospheric refractometry to define a new term, refractivity, symbolized by N and defined by,

$$N = (n - 1) \times 10^{+6} . \tag{1-3}$$

This allows a more convenient measure of index of refraction since the range of N (still using the more liberal upper limit for n) is given by

$$0.0 < N < 500.0 . \tag{1-4}$$

It is convenient to re-express Equation (1-1) by

$$f_o = \frac{K}{1 + N \times 10^{-6}} \tag{1-5}$$

$$\doteq K \left[1 - N \times 10^{-6} \right]$$

$$f_o + \Delta f_o \doteq K \left[1 - (N + \Delta N) \times 10^{-6} \right] \tag{1-6}$$

$$\doteq K \left[1 - N \times 10^{-6} \right] - K \Delta N \times 10^{-6}$$

$$\Delta f_o \doteq -K \Delta N \times 10^{-6} . \tag{1-7}$$

By Equation (1-1)

$$K = f_o n, \quad (1\text{-}8)$$

but since $n \doteq 1$,

$$K \doteq f_o, \quad (1\text{-}9)$$

so that

$$\frac{\Delta f_o}{f_o} \doteq -\Delta N \times 10^{-6} \quad . \quad (1\text{-}10)$$

Using the approximation that the center frequency is 10 gc (10×10^9 cps), it can be concluded that a change in N of one produces a change in f_o of 10 kc or 10^4 cps. In order to make use of such small percentage changes in resonant frequency, it is necessary that the measurement be made by comparison to a standard of frequency which is very stable. In the Crain (University of Texas) refractometer, a comparison is made by use of two stable oscillators, one of which is controlled by a sealed reference cavity, while the other is controlled by a ventilated sampling cavity. In bench-type operations, it is possible for the stable oscillator to be stabilized to approximately one part in 10^8 and, in airborne operation, one part in 10^6. With appropriate discriminators to evaluate the changes in difference frequency, it is possible to achieve index of refraction precision to 1 N-unit or better, depending on the physical location and the ranges of index of refraction to be encountered. In the Birnbaum (Bureau of Standards) type of refractometer, the signal from a single, frequency-modulated microwave source is sent through two

cavities, one of which is sealed as a reference, and the other of which is ventilated. The time difference between peaks of signals transmitted through the two cavities gives the frequency difference, provided the frequency varies linearly with time within each sweep.

In both types of refractometers, it is necessary that the measuring and comparing units be in reasonably close physical proximity to one another. Except for this one unfortunate requirement, both of these refractometer types are excellent devices which quite adequately perform the function for which they were designed.

More recently, Vetter[3] has developed what he called an "absolute refractometer." This refractometer is essentially the same as the Birnbaum unit, except that the reference cavity is continually tuned by insertion of a metal slug. This perturbation is controlled by a servomechanism system which is capable of correcting the resonant frequency such that the two cavities (reference and sampling) are kept either at the same frequency or at a fixed difference frequency. Because the sampling cavity is kept at the same frequency, the importance of linearity of other portions of the system is decreased sufficiently

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[3]Vetter, M. J., and W. B. Grant, "A Progress Report on NBS Airborne Microwave Refractometer," Nat'l Bureau of Standards Report 6086, January 1960.

so that it is feasible to place the sampling cavity in a vacuum to establish a zero refractivity reading and then interpret new correction settings of the perturbation slug as absolute refractivities without repeated calibration of the unit. This unit presumably suffers from the same problem mentioned for the other two, and further has the added weight of the servo-mechanism system and the inherent time lapse of correction for high-frequency changes in refractivity. If the high-frequency changes in refractivity are small in amplitude so that the cavity is never far from its corrected setting, the linearity problem is still at an acceptable minimum.

There are two further types of refractometers worthy of mention here. One is the University of Texas' expendable refractometer, designed by Andrew P. Deam[4], which is very similar in design to the Crain refractometer except that it operates at a frequency of approximately 400 megacycles, uses a coaxial type cavity, and allows separation between two elements: the measuring cavity with its associated electronic components and the comparison oscillator. The other is a Canadian development, primarily due to D. R. Hay and G. G. Bree[5]. This unit uses rather

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[4]Deam, A.P., An Expendable Atmospheric Radio Refractometer, EERL Report 108, University of Texas, 1959.

[5]Hay, D.R., and G.G.Bree, "Light Weight Refractometer," Defense Research Telecommunications Establishment, Report No. 1012, Ottawa, Canada, May 1959.

ordinary oscillators for both reference and measuring and, as a matter of fact, uses some of the same elements in both of the two oscillator circuits. The frequency of the measuring oscillator is determined in part by a capacitor which is ventilated, thereby changing the resonant frequency according to the dielectric constant of the material contained in the capacitor. This unit is very light and has great promise as an expendable unit capable of being balloon-borne in packages of essentially the same weight range as for standard radiosonde devices.

SECTION 2

A NEW SPECIAL REFRACTOMETER

Personnel of the University of New Mexico performed preliminary feasibility studies for the design of a refractometer capable of being packaged into the nosecone of an ARCAS missile to be carried aloft to sound the upper atmosphere to an altitude of approximately 200,000 feet. Subsequently, personnel of the University of New Mexico proposed a set of general design concepts which presumably would satisfy this requirement, and then proceeded to pursue a more detailed design of the device. Three additional reports discuss parts of the refractometer in greater detail than is given in this report.[6,7,8] Initially, weight figures were set at approximately 7.5 pounds, and the allowable space was as indicated in Figure 1 (approximately 165 cubic inches). Subsequently, the weight limitations imposed by technical aspects of the rocket have been revised upward. However, since the package is to be returned to earth by parachute and thus comes under regulations governing size of parachute-dropped packages, the weight has been revised downward to 6 pounds. As a result, the design has been

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[6] Dearholt, D. W., "Demodulation of a Special AM-FM Signal," Tech. Rpt.EE-34, Univ. of New Mexico, 1960.

[7] Jordan, J. C., and D. C. Thorn, "A Prototype Transmitter for a Microwave Refractometer," Tech. Rpt. EE-64, Univ. of New Mexico, 1961.

[8] Gilmer, R. O., and D.C.Thorn, "Some Design Criteria for Open-Ended Microwave Cavities," Tech.Rept.EE-65,Univ.of N.M.

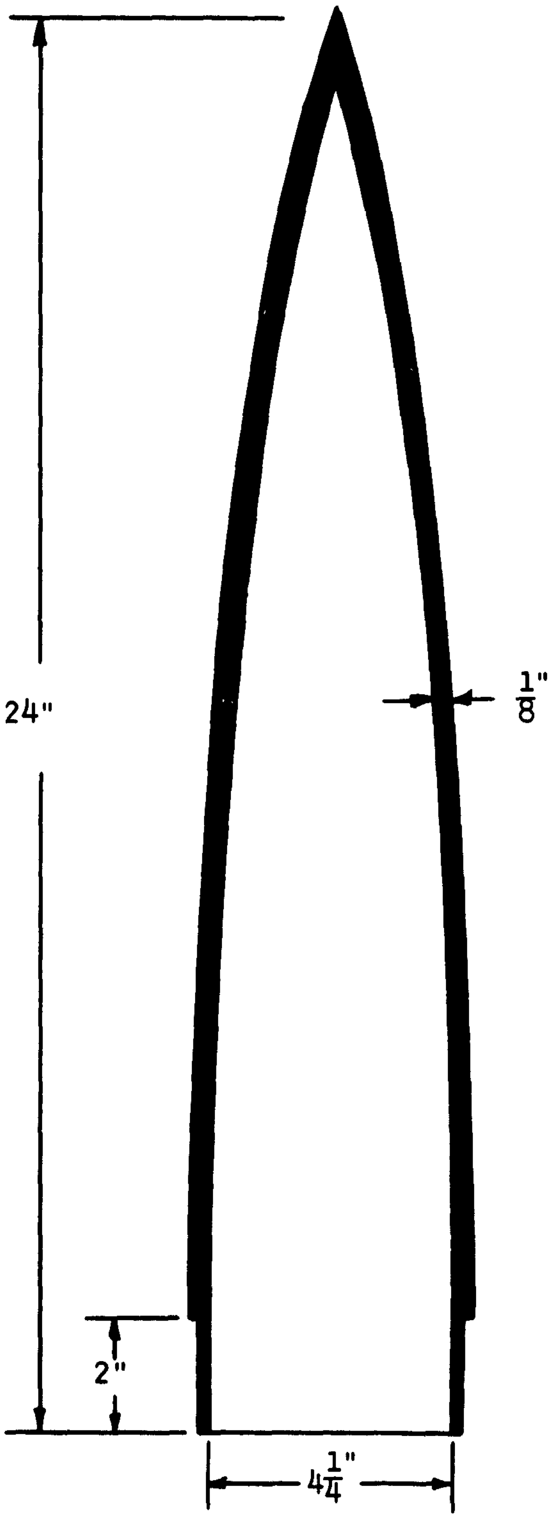

Figure 1. Cross-Section of the Nosecone

so severely constrained in weight that there is very little difficulty in terms of space availability.

2.1 Design Concept. Because of the severe weight and space limitations, coupled with the long range of the telemetry link, it was considered necessary that the refractometer be designed on a somewhat different principle from the previous types of refractometers. Previous types have in general been too bulky or too heavy for this application. However, both the University of Texas (Deam) and the Canadian (Hay) expendable refractometers might conceivably be adapted to the ARCAS configuration and weight limitations.

It is considered necessary that the sensing element be a cavity (either hollow or coaxial) or a capacitor. It was decided that the aerodynamic problems associated with either capacitor or coaxial cavity sensors would, for the rates of fall involved in this device, be such as to make them inadequate as sensors. As a result, a hollow cavity was chosen. A hollow cavity is an optimum compromise between size decrease due to increase in frequency and adequate ruggedness. The greater power capabilities of large, lower frequency devices indicated a choice of X-band for the device. This compares, of course, conveniently with both the Crain and Birnbaum units and allows the additional advantage of a choice of ready-made components from other types of refractometers, where such components are compatible.

Gilmer and Thorn attempted to extend the criteria of designing the hollow sensing cavities both electrically and aerodynamically.[9] Primarily, their report describes the electromagnetic problems involved in determining the proper waveguide size for a TE_{11N} sensing (open-ended) cavity operating in the X-band frequency range. The approach one may use for aerodynamic improvements of the sensing cavity is discussed. Also, Durrani[10] completed a survey of the techniques available for solving the waveguide discontinuity problems which arose in the designing of the sensing cavities.

The other important design philosophy which was used was that a minimum of equipment should be in the rocket-borne portion of the system even at the expense of an increased amount of complexity of equipment on the ground. It was concluded that a sensing or measuring cavity and a klystron (plus a power supply for the klystron) were the minimum essential elements. At this point a choice had to be made as to whether the klystron would be controlled by the cavity as in the Crain refractometer, or swept and fed through the cavity in a manner comparable to the Brinbaum

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[9] Gilmer, R. O. and D. C. Thorn, Op. Cit. p. 6

[10] Durrani, S. H., "Techniques for Solving Waveguide Discontinuity Problems with an Introduction to the Analysis of Waveguide Terminated by Longitudinal Fins," Technical Report EE-71, University of New Mexico, 1962.

device. To cause the cavity to govern the frequency of the klystron would require a feedback loop necessitating additional components of the air-borne unit and, as a result, it was decided to use the swept klystron technique.

If the klystron were repeller modulated by a sawtooth (or one of several other wave forms) voltage and the resulting frequency modulated microwave signal were then fed through a microwave cavity, the resulting FM and AM signal would have the required information associated with it. That is, the frequency at which the cavity was resonant would be established. The characteristic requirements imposed upon the cavity so that the FM signal is adequately amplitude modulated is described in detail by Dearholt.[11] Evaluation of such a signal would require that the amplitude peak corresponding to resonance be detected and "sharpened" by a pulse-shaping circuit so as to make a relatively narrow spike of voltage occur at a time corresponding to a particular frequency. It was concluded that instability, both of the sweeping circuit and of the natural (mechanically tuned) frequency of the klystron, would have to be accepted as a fact since the space and weight limitations would not allow feedback circuits for stabilization.

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[11] Dearholt, D. W., Op. Cit. p. 6

Thus, the final design concept of the airborne unit included a klystron, its power supply, a sweeping generator, a microwave cavity, and an antenna for radiating the output signal to the ground. No stability requirements were made on any component within this package, except that the mechanical frequency setting of the klystron should not be changed too much by pressure and temperature. Thermally induced drift of the cavity must either be eliminated or measured.

A complete study of the design, development and fabrication details of an airborne transmitter that meets the given requirements is described by Jordan and Thorn.[12] This transmitter and its various components are discussed in detail. The physical environment resulting from the rocket propulsion system used to elevate the transmitter and the extreme altitude is discussed along with proposed precautions to eliminate any harmful effects. Appropriate weight specifications of the transmitter components are established so that the maximum weight conforms to the limitations imposed by the Federal Aviation Agency.

The ground station was designed to be capable of taking the special signal from the flight package and interpreting it in terms of relative index of refraction. The size, plus the altitude to which the airborne unit is to be

[12] Jordan, J. C., and D. C. Thorn, Op. Cit. p. 6

elevated, requires a separate radar to be used to locate and track the unit. A surveillance radar which contains the basic ground electronics is used as a slave to the tracking unit.

Problems of signal power level at the ground may cause some difficulty. The use of a traveling-wave-tube amplifier (chosen because of its signal-to-noise ratio) or other type of amplifier can be used to increase the signal strength. A bandwidth of approximately 7 mc is needed in the input amplifier to pass the AM-FM signal. Then the signal is mixed with a constant frequency signal obtained from an ultra-stable local oscillator.

After the input signal is mixed with the local oscillator signal, the difference signal is fed into circuitry capable of demodulating the special FM-AM signal. The demodulation equipment is so designed that the relative frequency of the amplitude peaks are known. Dearholt describes a unit designed to shape the amplitude modulated portion of the signal and to form a "spike" from the maximum or minimum of the signal. The frequency portion of the signal is fed into an intermediate frequency amplifier, clipper, and discriminator. Both outputs which contain the desired information are then fed onto recording equipment so as to obtain the relative index of refraction.

Although the design criteria discussed were imposed by a requirement for a rocket-borne unit, it appears quite reasonable to anticipate that the development (which has

resulted thus far in a bench-model prototype) would lend itself quite admirably to several other applications in refractometry. For instance, it would seem that the rocket-borne portion of the refractometer could be mounted on a light aircraft and/or drone to feed information back to the ground unit. Such an application would allow, for instance, a drone to fly over inaccessible territory to obtain index of refraction data which would be difficult to obtain otherwise.

Additionally, the separate character of the airborne and ground-based portions of this refractometer makes it appear quite feasible to make use of the same scheme with multiple "airborne" units and one "ground-based" unit so as to obtain index of refraction data from multiple points, or multiple paths of travel of the airborne units by switching the ground unit from detection of one to the other.

2.2 Refractometer Block Diagram and General Function:

The over-all block diagram of the refractometer is shown in Figure 2. It is probably most convenient to consider the action of the refractometer by considering diagram blocks in turn.

Block 1 (Power Supply): In the rocket-borne design in particular, this refers to both the batteries and the converting equipment to supply the voltages required by the sweep oscillator and the klystron.

Block 2 (Sweep Oscillator): This oscillator is designed to be a sawtooth voltage output device; however, the exact nature of the signal which it puts out is not critical so long as it does sweep voltage

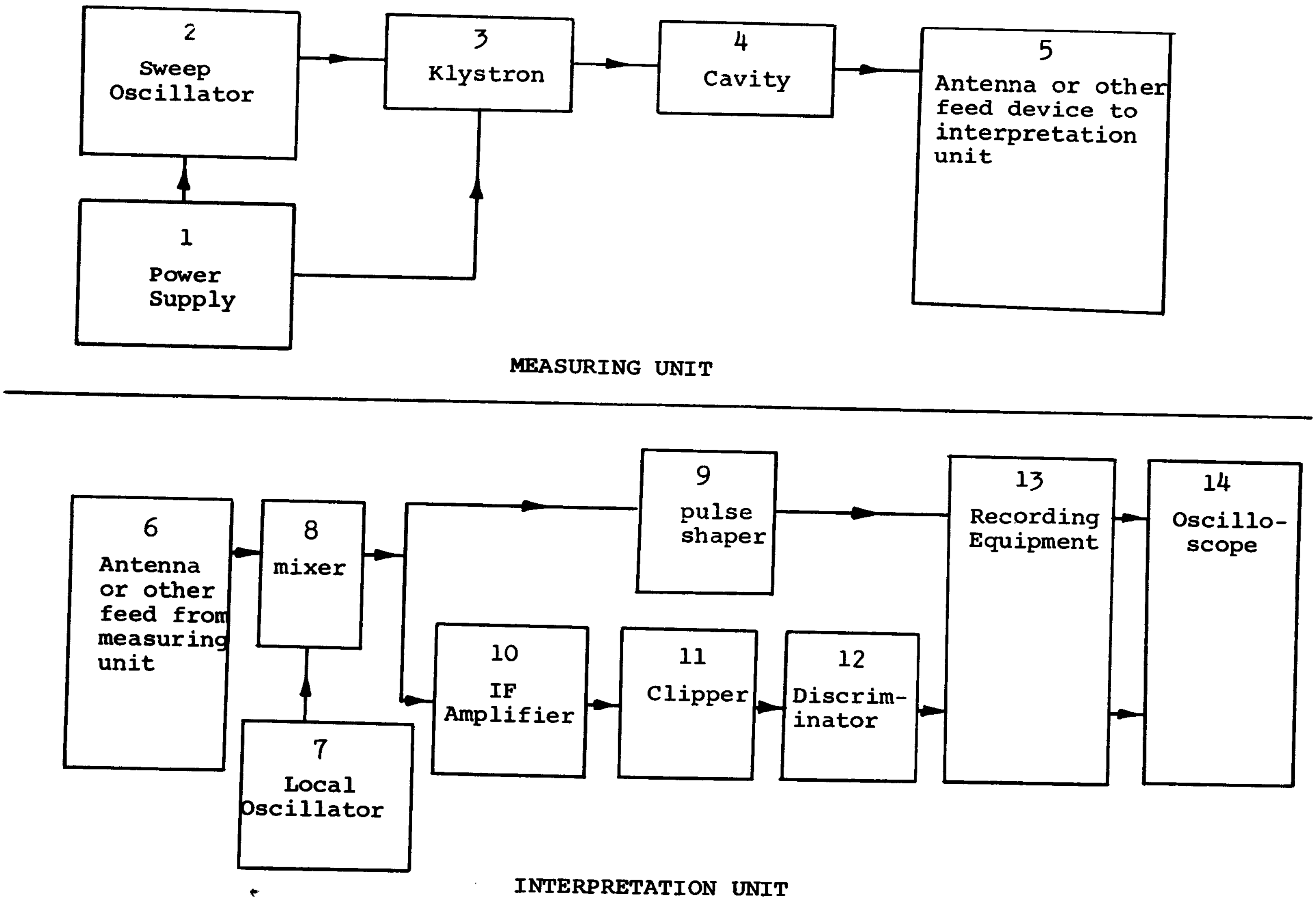

Figure 2
Refractometer Block Diagram

over a range as a function of time. Its output is applied as modulation to the repeller of the klystron.

Block 3 (Klystron): The klystron (or equivalent voltage controlled oscillator) produces a microwave output with a center frequency in the X-band range with a frequency modulation of approximately 5-7 megacycles. It is intended that the klystron be operating near the center of its most powerful mode. By operating at the center of a mode, the sweeping voltage applied to the repeller primarily produces frequency modulation with a minimum amount of amplitude modulation.

Block 4 (Cavity): The output of the klystron is fed to the modulating cavity, which modulates the klystron output amplitude according to the cavity's resonant frequency. There are two alternate configurations feasible for the cavity. The signal can be fed through the cavity so that the cavity is used as a transmission device. In such an arrangement, the resonant frequency is the frequency at which the maximum signal is transmitted. Alternately, the cavity absorbs energy at resonance and thus produces a minimum output at resonance.

Block 5 (Antenna or equivalent): In the rocket-borne design, the antenna is required to relay the amplitude and frequency modulated signal containing cavity resonance information to the ground unit. In non-rocket-borne applications, of course, a coaxial or waveguide connection to the interpretation unit input would be practical. . It is interesting to note that an early design possibility whicn presented itself for the rocket-borne version was the use of the parachute as a quasi-parabolic reflecting antenna. The parachute used in the experiments with the rocket device for which this equipment was originally conceived is normally metalized to present a better target for ground

observing radars. With the parachute approximately twenty feet in diameter, and approximately parabolic in shape, it appeared at first that this would be a very desirable arrangement with the rocket package feed horn placed approximately at the focus. It was later concluded, however, that such an arrangement would not be feasible since the antenna pattern would be so very tight (approximately 0.4 degrees between 3-DB points) that even a very slight deviation in orientation due to sway would put the main lobe off of the ground based receiver. It was one of those peculiar situations in which antenna gain would be highly desirable if properly used, but in which such gain was not feasible.

Block 6 (Antenna and Microwave Amplifier): In the rocket design, it was considered desirable to have a steerable antenna such as would be found on a radar set to give as high gain as possible in the ground unit. Block 6 includes both this antenna and whatever microwave frequency amplifying units might be necessary.

Block 7 (Local Oscillator): In essentially all microwave refractometers intended for atmospheric use, the final limit of accuracy resides with the stability associated with the local oscillator or other comparison device. Since the refractivity of atmospheric gases varies by only a few hundred (i.e., a few hundred parts per million for refractive index), it is necessary that the local oscillator be capable of stabilities such that the refractivity changes are not masked. That is to say, for an upper limit of accuracy of one N unit, (i.e., one part per million for refraction) the local oscillator would have to have a stability of one part per million. This, of course, assumes other ideal equipment. Oscillators, which have stabilities of one part in 10^8, are in reasonable availability. Specifically, it was intended to use the Laboratory for Electronics

Model 814-X-1, which was the same stable oscillator used for bench test purposes.

Block 8 (Mixer): In microwave circuits, the same types of crystals are often used both as mixer and as detectors. As will be seen from a discussion of the subsequent blocks that it was necessary to have both of these actions fulfilled in the interpretation unit. Tests showed the feasibility of using a single crystal to perform both operations simulatenously. This gave the obvious advantage that less crystal noise was introduced into the system. Somewhat less obvious, perhaps, is the fact that there is less power loss when a single crystal is used for both functions. In this particular application, it was necessary to obtain the amplitude modulation envelope simultaneously while obtaining the frequency modulation signal at an intermediate frequency of approximately 40 megacycles. A single crystal used for mixing purposes would have some of its output energy in the form of AM envelope (in this case in the order of one kilocycle per second) as well as the sum and difference of the frequencies and other incidental double sums, etc. If the intermediate frequency was the desired signal, other frequency components, including the amplitude modulation, would be rejected; and thus basically lost. Thus, the low frequency amplitude modulation signal which would have otherwise been rejected is a useful output.

Block 9 (Pulse Shaper): This unit serves to take the amplitude modulated signal which is a slightly distorted sinusoidal signal, and shape it so that there is a definite "spike" associated with the maximum or minimum of the amplitude modulated signal. As it was originally conceived, the pulse shaper would have been sensitive to the maximum. In the later versions, it would be modified to sense the minimum.

Blocks 10, 11, 12(Intermediate Frequency Amplifier, Clipper, Discriminator): These are relatively standard types of items except for the fact that they are wide band. Since the oscillator of Block 2 is swept approximately 500 parts per million, at approximately 10,000 megacycles, there is a 5 megacycle sweep; blocks 10, 11 and 12 must be capable of handling this 5 megacycle sweep, centered on an intermediate frequency of approximately 40 megacycles. Thus the percentage band width required is somewhat higher than ordinary. As it happens, this entire section of the interpretation unit is compatible to the so-called "metering strip" of the Crain refractometer. Consequently, such a metering strip was purchased from Aerielectronics, Inc. It is believed that this unit is quite satisfactory for our purposes without additional modification.

Block 13 (Recording Equipment): Depending upon the location and immediate requirements, the output of Blocks 9 and 12 can be recorded as is appropriate. Final interpretation, however, would still necessitate some type of operation similar to that described below unless the interpretation is to be done by a computer.

Block 14 (Oscilloscope): Whether an oscilloscope would actually be attached at the time of taking of data is perhaps questionable. However, it is most convenient to understand the operation of the interpretation unit in terms of an oscilloscope. The output of Block 12 (the Discriminator) is almost, but not quite, a duplication of the sweep oscillator voltage which was originally applied to the klystron. Actually, a klystron is not quite a linear (frequency-to-input-voltage) device, and consequently even an ideal discrimination of the output frequency would not reproduce exactly the sweeping signal. However, it is not the sweeping signal which is desired here, but

rather the voltage which is proportional to the actual frequency of the klystron. This of course, is what is developed by the discriminator if the discriminator is ideal. If this voltage then is applied to the X-axis deflection plates of the oscilloscope, the oscilloscope beam horizontal position is proportional to incoming frequency. If at the same time the output of Block 9 is applied to the vertical deflection plates and to the amplitude control of the oscilloscope, it is possible to obtain a slight "blip" at a horizontal position corresponding to the frequency of resonance of the detecting cavity. Since the output of the pulse shaper is also applied to the amplitude control on the oscilloscope, there is no signal on the face of the scope, except at the position corresponding to the resonant frequency of the sampling cavity. Thus the "blip" will move back and forth across the face of the oscilloscope as the resonant frequency of the cavity is altered. If this resonant frequency is altered as a function only of the index of refraction of the sampled gases therein, the position of the "blip" on the oscilloscope becomes a measure of index refraction.

SECTION 3

RESULTS

The entire refractometer described in this report has been bench tested. All operations have been successfully carried out with both a direct wave guide coupling between the measuring and interpretation units and with a short air path between these units. It has been shown that the readings obtained from this unit are directly dependent upon index refraction, since modification of the index refraction contained within the cavity has indeed caused modification in "blip" position on the face of the oscilloscope. It has not, however, been possible to calibrate the instrument at this time, nor has it been feasible to attempt a measurement of instrumental errors.

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